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THERMAL DIFFUSIVITY OF FROZEN SOIL. (U)

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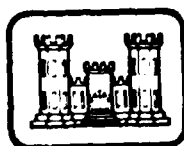
THERMAL DIFFUSIVITY OF FROZEN SOIL

F.D. Haynes, D.L. Carbee and D.J. VanPelt

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Preface

This report was prepared by F.D. Haynes, Materials Research Engineer, of the Ice Engineering Research Branch, and D.L. Carbee, Supervisory Civil Engineering Technician, and D.J. VanPelt, Civil Engineering Technician, of the Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A161101A91D, In-House Laboratory Independent Research, Work Unit 261, Determination of Thermal Diffusivities for Frozen Soils.

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THERMAL DIFFUSIVITY OF FROZEN SOIL

F.D. Haynes, D.L. Carbee and D.J. VanPelt

INTRODUCTION

Knowledge of the thermal properties of frozen soil has become more important as construction activity in cold regions increases. Data on frozen soils are needed for the design of pipelines and earth-fill dams built on permafrost. Considerable interest is also being shown in freeze-back techniques for excavation in moderate climates.

Early work on the thermal properties of frozen soil was done by Kersten (1949). Higashi (1953) studied the thermal conductivity and thermal diffusivity of frozen soils. The thermal diffusivity of silt, clay and ice was investigated by Wolfe and Thieme (1964). A model for heat conduction in frozen soil was developed by McGaw (1968). Penner (1970) used a thermal probe to study the thermal conductivity of clay and silt between 0 and -22°C , and Penner et al. (1975) determined the thermal conductivity of 10 soils between $+5$ and -25°C . Johansen (1975) developed a method for predicting the thermal conductivity of soils based on empirical relations. The specific heat for dry soils between -73° and $+27^{\circ}\text{C}$ was determined by Kay and Goit (1975). Finite element methods for approximating heat transfer in soil-water-ice systems have been developed by many researchers, e.g. Mohan (1975).

Previous work on the thermal properties of frozen soil has been limited with respect to temperature and moisture content. Our present study extends the available data to temperatures of -50°C at moisture contents from dry to saturated. We found the specific heats for 10 materials including Fairbanks silt, Hanover varved clay and Ottawa sand by using a differential scanning calorimeter and the thermal conductivities for Fairbanks silt, Ottawa sand and Hanover varved clay by using the guarded hot plate method (ASTM C-177-71). Our results are compared with those of previous investigations, and thermal diffusivities are given for the soils over the range of test variables.

The thermal diffusivity of a soil is necessary for analyzing transient heat transfer conditions, while the thermal conductivity is necessary for steady-state conditions. When construction is planned on frozen soil, the site-specific soil should be tested to determine its thermal properties. However, the data contained here should prove useful for estimation purposes.

DETERMINATION OF SPECIFIC HEATS

Specific heat determinations were made with a Perkin-Elmer differential scanning calorimeter, model DSC-1, (Fig. 1). We determined the specific heat values by measuring the power required to change the temperature of a



Figure 1. Perkin-Elmer differential scanning calorimeter with nitrogen purged hood.

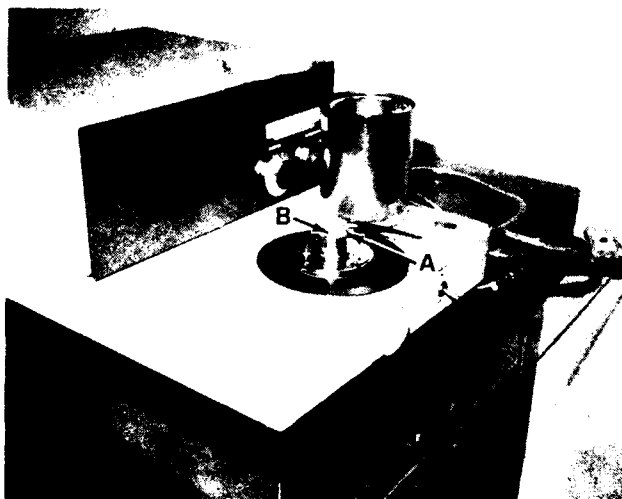


Figure 2. Calorimeter test sample holder showing both the test (A) and reference (B) samples.

test sample and a reference sample being scanned at the same time and at the same constant temperature rate. This difference in power was recorded on a strip chart recorder.

The calorimeter can scan at temperature rates from 0.625°C/min to 80°C/min. The higher the rate, the greater the differential power required, but fast rates reduce the resolution in determining the specific heat at any set temperature. The scanning rate for this study was 20°C/min.

In these tests, the cover for the sample holder was filled with liquid nitrogen to allow specific heat measurements to be made at temperatures below -50°C. When ambient humidity became a problem at the low temperatures, an enclosure with a continuously circulating nitrogen supply was erected over the sample holder of the calorimeter. This eliminated the moisture problem.

The specific heat samples weighed between 25 and 100 mg. The sample weights were determined to 0.1 mg. Only fine-grained soils, i.e. those passing the no. 20 mesh (0.841-mm) sieve, could be tested with this calorimeter. The mechanical properties and gradation curves of the test soils are given in Appendix A.

The sample containers were aluminum pans 0.635 cm in diameter and 0.254 cm deep with covers that could be placed in a container crimping apparatus and sealed to prevent loss of moisture during a test.

Once the samples had been placed in the containers, weighed, and sealed, they were put in the calorimeter test holder beside the reference sample (Fig. 2). The liquid nitrogen cover pan was placed over the top of the container and the sample temperature was reduced and allowed to stabilize. Then the test sample and reference sample were changed to -50°C at a 20°C/min rate.

The method of calculating the specific heat using the scanning calorimeter is given in Appendix B. The required power was recorded (Fig. B1), and then successive tests were done at 15°C intervals up to +35°C. The test results are given in Table 1. Figures 3-13 show the results of the specific heat measurements.

DETERMINATION OF THERMAL CONDUCTIVITY

Materials

The materials tested in this portion of the study were Fairbanks silt (ML) with a specific gravity of 2.70, CRREL varved clay (CL-ML) with a specific gravity of 2.75, and Ottawa sand (20-30) with a specific gravity of 2.65. We tested the silt and clay soils with samples in 1) air dried, 2) optimum moisture, and 3) saturated conditions and the sand in 1) air-dried and 2) surface wet conditions.

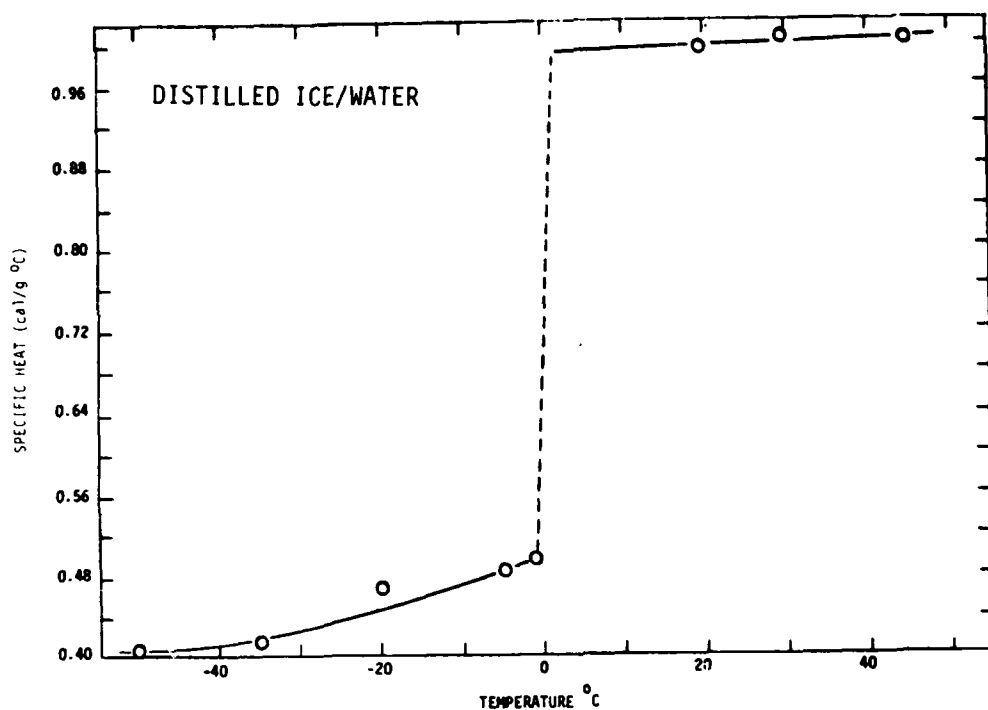


Figure 3. Specific heat of distilled ice/water.

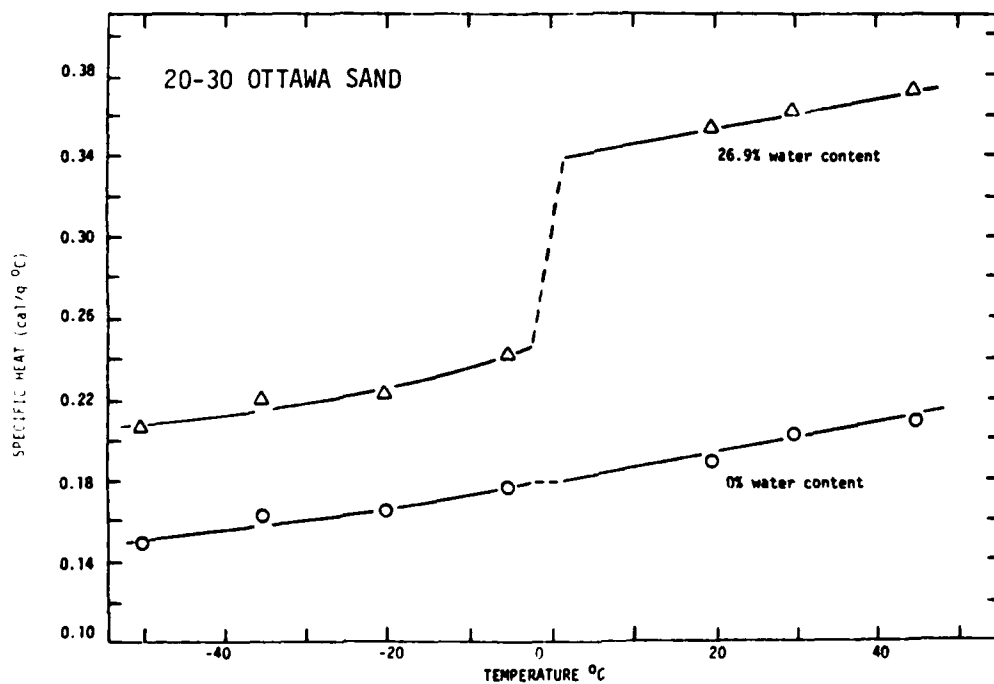


Figure 4. Specific heat of 20-30 Ottawa sand.

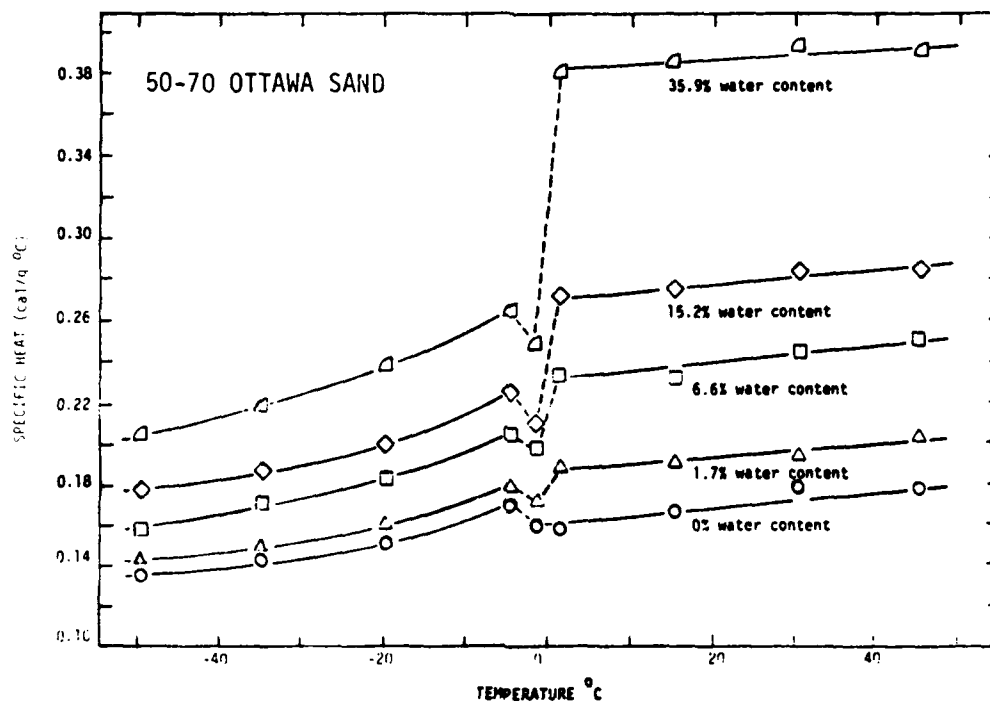


Figure 5. Specific heat of 50-70 Ottawa sand.

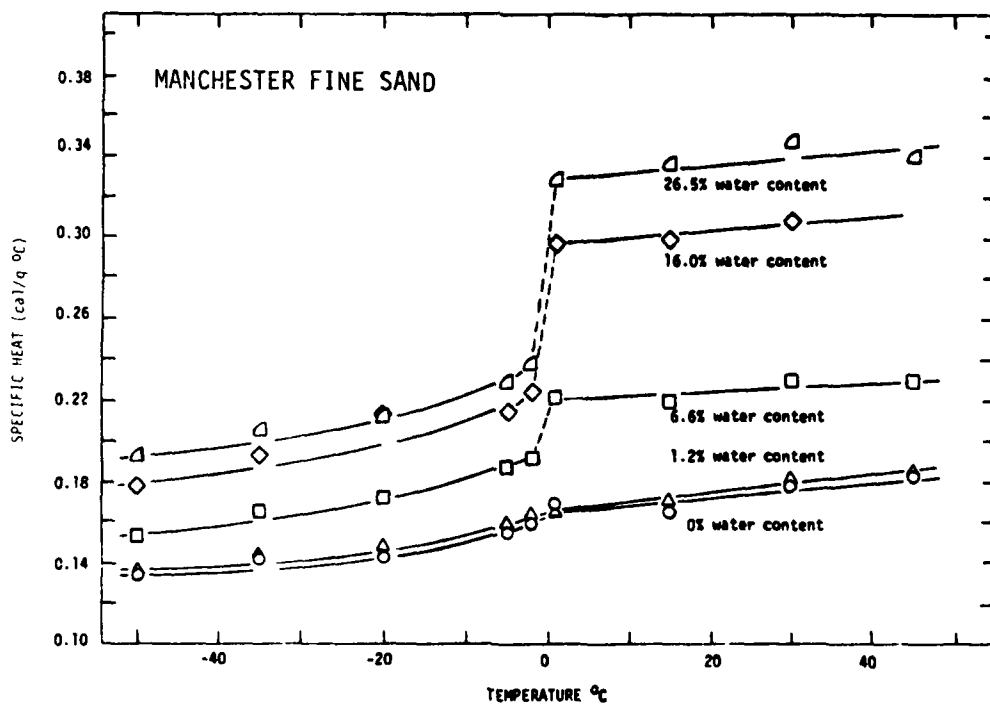


Figure 6. Specific heat of Manchester fine sand.

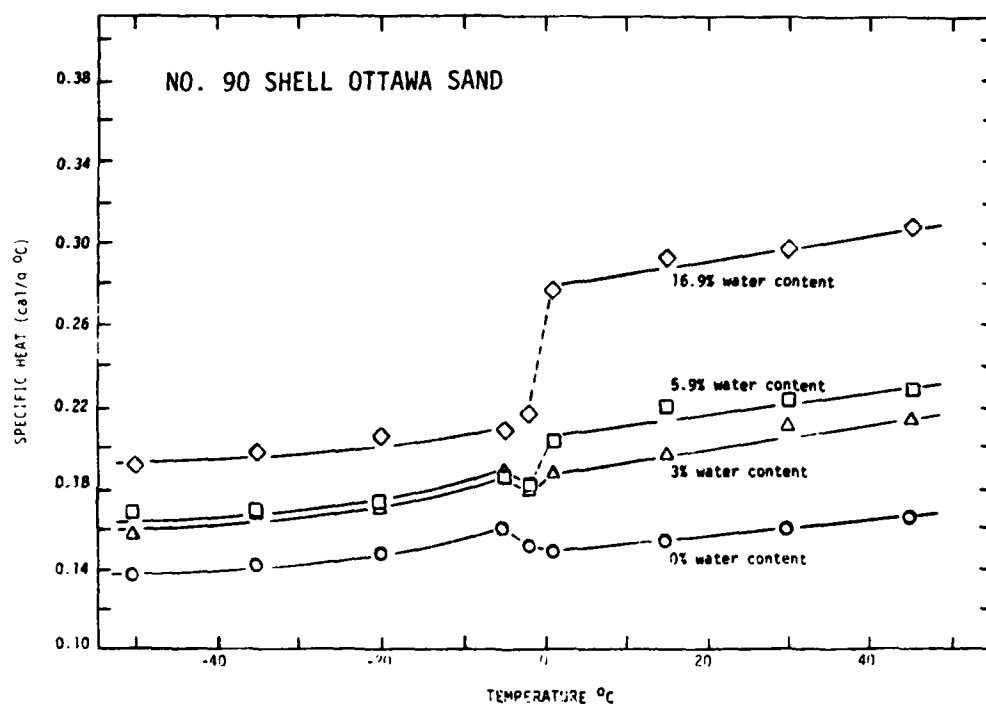


Figure 7. Specific heat of no. 90 Shell Ottawa sand.

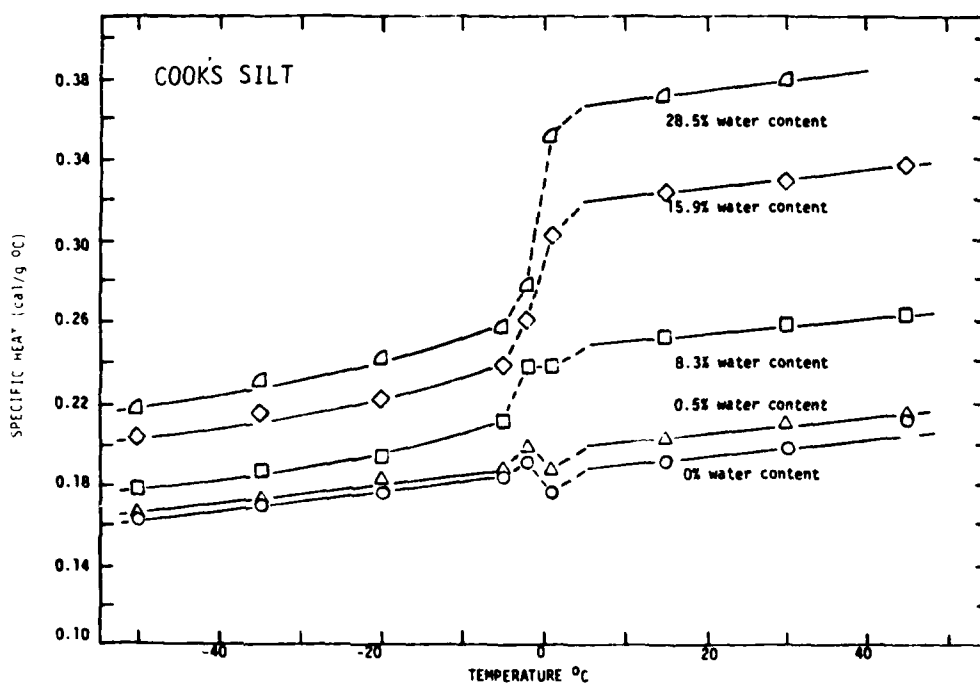


Figure 8. Specific heat of Cook's silt.

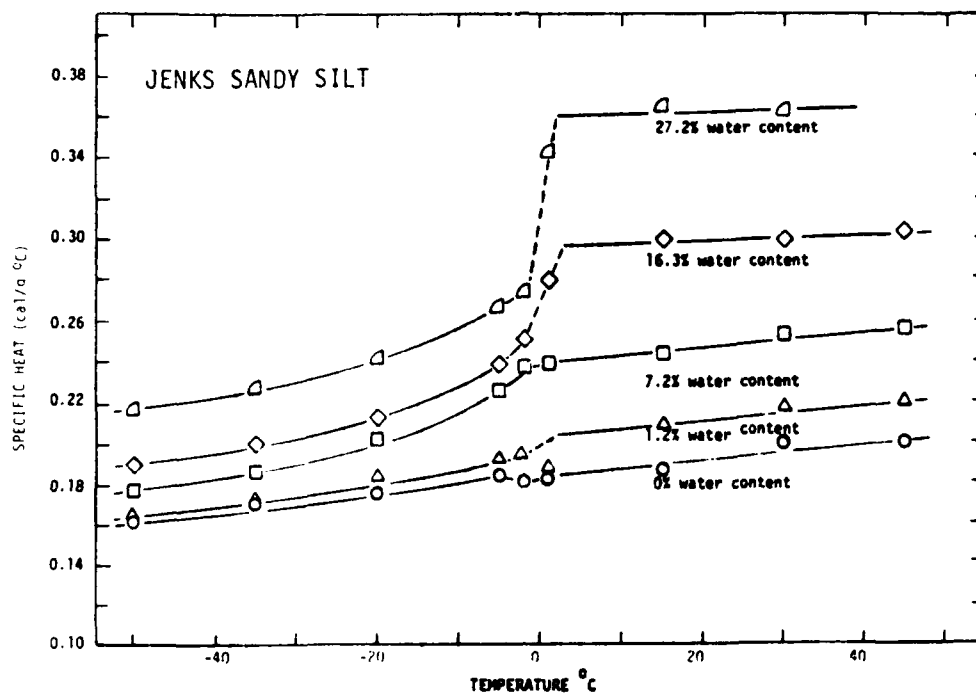


Figure 9. Specific heat of Jenks sandy silt.

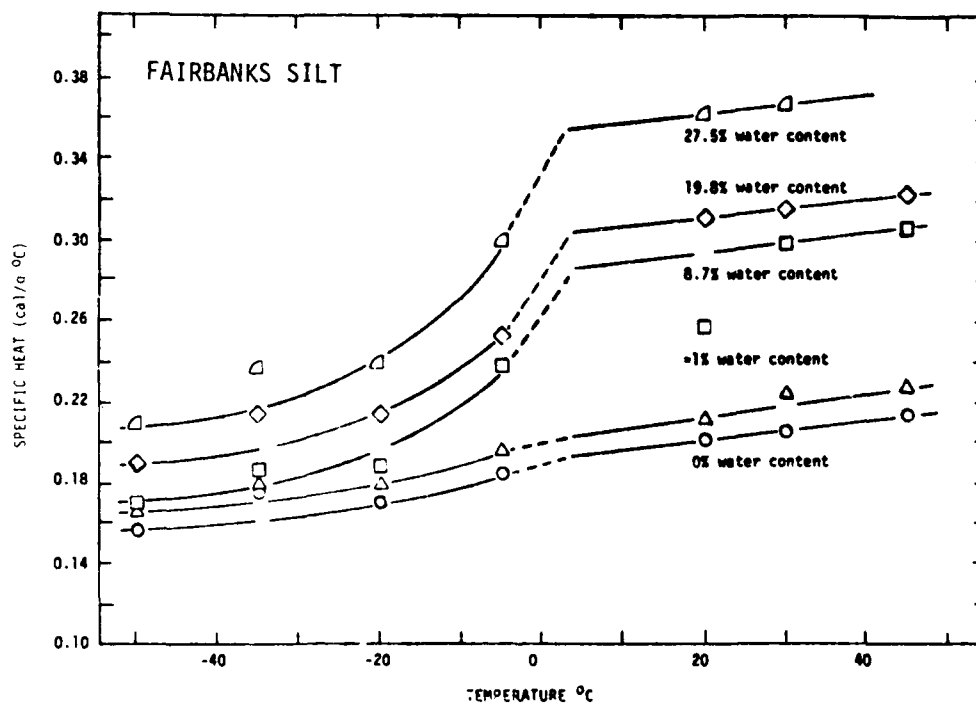


Figure 10. Specific heat of Fairbanks silt.

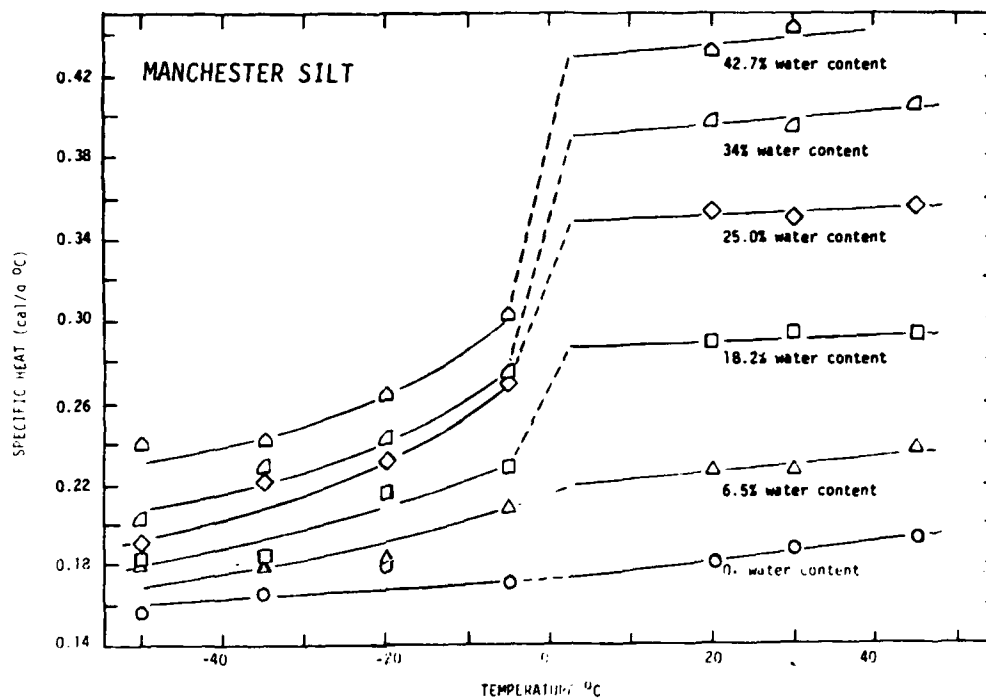


Figure 11. Specific heat of Manchester silt.

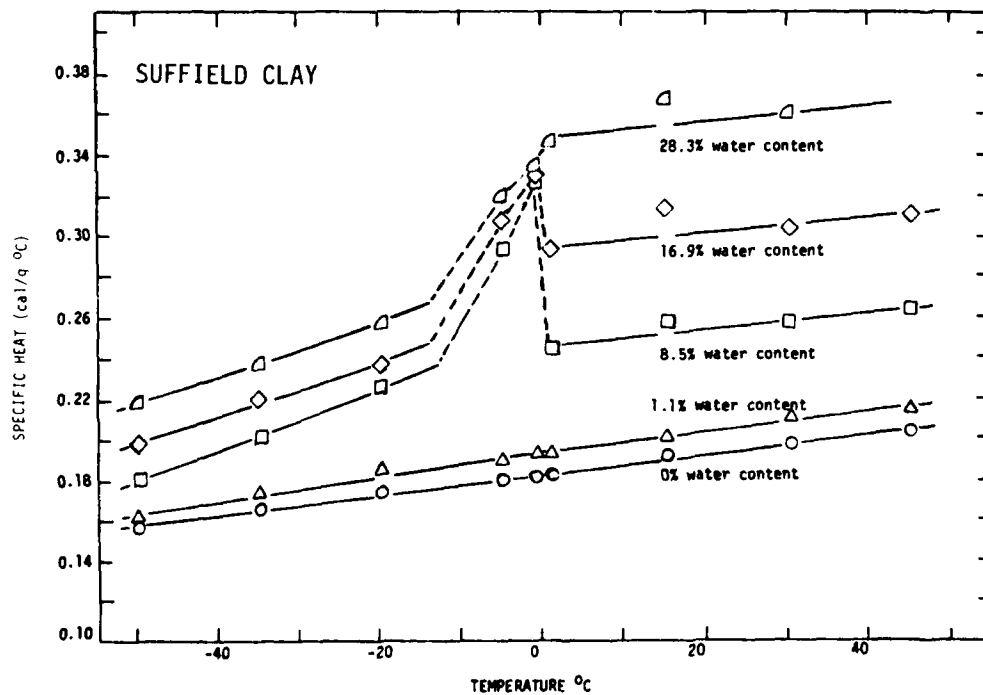


Figure 12. Specific heat of Suffield clay.

Table 1. Results of the specific heat determinations.

| Sample No. | Wet wt (mg) | Dry wt (mg) | Water content % | Specific heat (cal/g °C) | | | | | | | | | | |
|------------------------------|-------------|-------------|-----------------|--------------------------|------|------|------|------|------|------|------|------|-------|-------|
| | | | | Temperature (°C) | | | | | | | | | | |
| | | | | -50 | -35 | -20 | -5 | -2 | -1 | +1 | +15 | +20 | +30 | +45 |
| <u>Ice/Water</u> | | | | | | | | | | | | | | |
| I-1 | 13.3 | - | - | .407 | .417 | .469 | .486 | - | .497 | .960 | - | .993 | 1.006 | 1.000 |
| <u>20-30 OTTAWA SAND</u> | | | | | | | | | | | | | | |
| OWS-air dry | 33.2 | 33.2 | 0 | .130 | .143 | .146 | .158 | - | - | - | .170 | .183 | .188 | .188 |
| OWS-sur-face wet | 35.9 | 28.3 | 26.9 | .185 | .200 | .203 | .222 | - | - | - | .333 | .342 | .351 | .351 |
| <u>50-70 OTTAWA SAND</u> | | | | | | | | | | | | | | |
| OWS-1 | 29.7 | 29.7 | 0 | .135 | .143 | .151 | .169 | .158 | - | .157 | .165 | - | .179 | .177 |
| OWS-2 | 23.7 | 23.3 | 1.7 | .142 | .150 | .159 | .177 | .170 | - | .187 | .189 | - | .193 | .201 |
| OWS-3 | 29.1 | 27.3 | 6.6 | .157 | .170 | .182 | .203 | .195 | - | .232 | .231 | - | .243 | .250 |
| OWS-4 | 28.7 | 24.9 | 15.2 | .176 | .186 | .199 | .224 | .208 | - | .270 | .273 | - | .282 | .284 |
| OWS-5 | 34.8 | 25.6 | 35.9 | .203 | .217 | .237 | .263 | .245 | - | .381 | .384 | - | .392 | .390 |
| <u>MANCHESTER FINE SAND</u> | | | | | | | | | | | | | | |
| MFS-1 | 21.9 | 21.9 | 0 | .137 | .144 | .145 | .157 | - | .162 | .171 | .168 | - | .181 | .185 |
| MFS-2 | 25.8 | 25.5 | 1.2 | .137 | .146 | .150 | .159 | - | .166 | .167 | .172 | - | .182 | .185 |
| MFS-3 | 24.2 | 22.7 | 6.6 | .154 | .167 | .174 | .189 | - | .193 | .224 | .221 | - | .231 | .231 |
| MFS-4 | 38.4 | 33.1 | 16.0 | .180 | .196 | .216 | .217 | - | .226 | .299 | .301 | - | .310 | - |
| MFS-5 | 34.4 | 27.2 | 26.5 | .194 | .207 | .213 | .231 | - | .240 | .330 | .338 | - | .349 | .341 |
| <u>#90 SHELL OTTAWA SAND</u> | | | | | | | | | | | | | | |
| SOWS-1 | 25.8 | 25.8 | 0 | .140 | .145 | .151 | .163 | .153 | - | .152 | .157 | - | .162 | .168 |
| SOWS-2 | 24.2 | 23.5 | 3.0 | .159 | .170 | .175 | .192 | .183 | - | .190 | .199 | - | .212 | .216 |
| SOWS-3 | 32.5 | 30.7 | 5.9 | .171 | .171 | .174 | .188 | .182 | - | .205 | .223 | - | .225 | .231 |
| SOWS-4 | 36.6 | 31.3 | 16.9 | .194 | .200 | .208 | .211 | .219 | - | .279 | .295 | - | .299 | .310 |

Table 1. (Cont'd).

| Sample No. | Wet wt (mg) | Dry wt (mg) | Water content % | Temperature (°C) | | | | | | | | | | |
|------------------|-------------|-------------|-----------------|------------------|------|------|------|------|------|------|------|------|------|------|
| | | | | -50 | -35 | -20 | -5 | -2 | -1 | +1 | +15 | +20 | +30 | +45 |
| COOK'S SILT | | | | | | | | | | | | | | |
| CS1-1 | 22.6 | 22.6 | 0 | .166 | .172 | .183 | .187 | - | .199 | .187 | .202 | - | .209 | .213 |
| CS1-2 | 21.9 | 21.8 | 0.5 | .164 | .171 | .176 | .185 | - | .191 | .176 | .190 | - | .197 | .210 |
| CS1-3 | 26.0 | 24.0 | 8.3 | .178 | .187 | .194 | .211 | - | .239 | .238 | .252 | - | .258 | .263 |
| CS1-4 | 31.3 | 27.0 | 15.9 | .203 | .215 | .222 | .239 | - | .261 | .303 | .324 | - | .328 | .337 |
| CS1-5 | 39.2 | 30.5 | 28.5 | .217 | .231 | .243 | .257 | - | .278 | .351 | .371 | - | .378 | - |
| JENKS SANDY SILT | | | | | | | | | | | | | | |
| JSS-1 | 18.7 | 18.7 | 0 | .161 | .172 | .174 | .183 | .180 | - | .182 | .186 | - | .199 | .200 |
| JSS-2 | 17.5 | 17.3 | 1.2 | .152 | .171 | .183 | .191 | .193 | - | .186 | .208 | - | .217 | .220 |
| JSS-3 | 16.4 | 15.3 | 7.2 | .176 | .185 | .200 | .225 | .236 | - | .238 | .243 | - | .252 | .256 |
| JSS-4 | 30.7 | 26.4 | 16.3 | .189 | .199 | .212 | .238 | .250 | - | .279 | .299 | - | .299 | .302 |
| JSS-5 | 39.8 | 31.3 | 27.2 | .214 | .226 | .241 | .267 | .273 | - | .342 | .363 | - | .361 | - |
| FAIRBANKS SILT | | | | | | | | | | | | | | |
| FBS-1 | 20.9 | 20.9 | 0 | .157 | .176 | .170 | .184 | - | - | - | - | .201 | .205 | .213 |
| FBS-2 | 19.7 | - | ≈1 | .167 | .179 | .179 | .195 | - | - | - | - | .211 | .224 | .226 |
| FBS-3 | 27.5 | 25.3 | 8.7 | .168 | .197 | .198 | .238 | - | - | - | - | .257 | .298 | .305 |
| FBS-4 | 26.0 | 21.7 | 19.8 | .190 | .214 | .214 | .253 | - | - | - | - | .312 | .315 | .322 |
| FBS-5 | 42.6 | 33.4 | 27.5 | .209 | .237 | .238 | .300 | - | - | - | - | .362 | .367 | - |
| MANCHESTER SILT | | | | | | | | | | | | | | |
| MS1-1 | 13.0 | 13.0 | 0 | .157 | .166 | .180 | .171 | - | - | - | - | .181 | .187 | .193 |
| MS1-4 | 19.6 | 18.4 | 6.5 | .179 | .181 | .183 | .207 | - | - | - | - | .225 | .225 | .236 |
| MS1-5 | 29.2 | 24.7 | 18.2 | .181 | .184 | .215 | .227 | - | - | - | - | .288 | .294 | .292 |
| MS1-8 | 33.0 | 26.4 | 25.0 | .193 | .220 | .229 | .265 | - | - | - | - | .353 | .350 | .355 |
| MS1-9 | 39.4 | 29.4 | 34.0 | .202 | .228 | .241 | .272 | - | - | - | - | .397 | .393 | .405 |
| MS1-10 | 25.4 | 17.8 | 42.7 | .239 | .240 | .263 | .301 | - | - | - | - | .431 | .442 | - |

Table 1. (Cont'd).

| Sample No. | Wet wt (mg) | Dry wt (mg) | Water content % | Temperature (°C) | | | | | | | | | | |
|--------------------------|-------------|-------------|-----------------|------------------|------|------|------|----|------|------|------|------|------|------|
| | | | | -50 | -35 | -20 | -5 | -2 | -1 | +1 | +15 | +20 | +30 | +45 |
| <u>SUFFIELD CLAY</u> | | | | | | | | | | | | | | |
| SFC-1 | 21.5 | 21.5 | 0 | .157 | .166 | .174 | .180 | - | .181 | .182 | .191 | - | .196 | .202 |
| SFC-2 | 19.1 | 18.9 | 1.1 | .162 | .175 | .184 | .188 | - | .192 | .192 | .200 | - | .209 | .212 |
| SFC-3 | 25.5 | 23.5 | 3.5 | .181 | .202 | .226 | .293 | - | .329 | .244 | .257 | - | .256 | .262 |
| SFC-4 | 34.5 | 29.5 | 16.9 | .199 | .220 | .238 | .307 | - | .326 | .293 | .313 | - | .303 | .309 |
| SFC-5 | 38.5 | 30.0 | 28.3 | .219 | .237 | .257 | .319 | - | .333 | .345 | .367 | - | .359 | - |
| <u>CRREL VARVED CLAY</u> | | | | | | | | | | | | | | |
| CVC-1 | 13.7 | 13.7 | 0 | .146 | .160 | .171 | .164 | - | - | - | - | .173 | .194 | .194 |
| CVC-2 | 20.9 | 20.8 | 0.5 | .141 | .159 | .166 | .190 | - | - | - | - | .211 | .213 | .220 |
| CVC-3 | 28.7 | 25.6 | 12.1 | .201 | .209 | .225 | .268 | - | - | - | - | .267 | .265 | .274 |
| CVC-4 | 21.7 | 18.4 | 17.9 | .190 | .198 | .219 | .149 | - | - | - | - | .283 | .286 | .295 |
| CVC-5 | 36.4 | 28.4 | 28.2 | .214 | .226 | .244 | .281 | - | - | - | - | .346 | .343 | .356 |

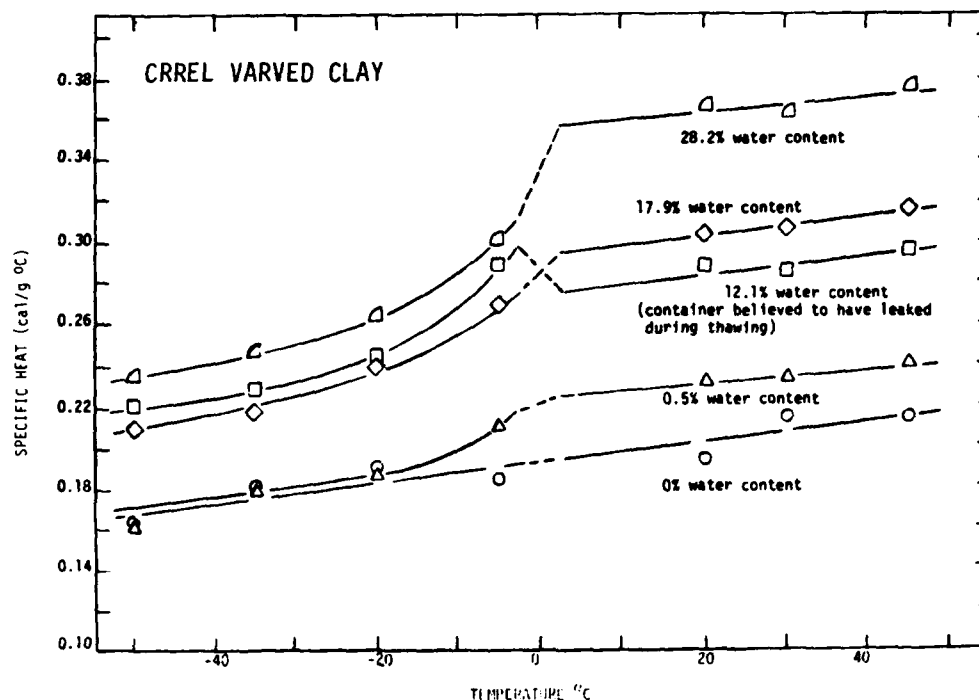
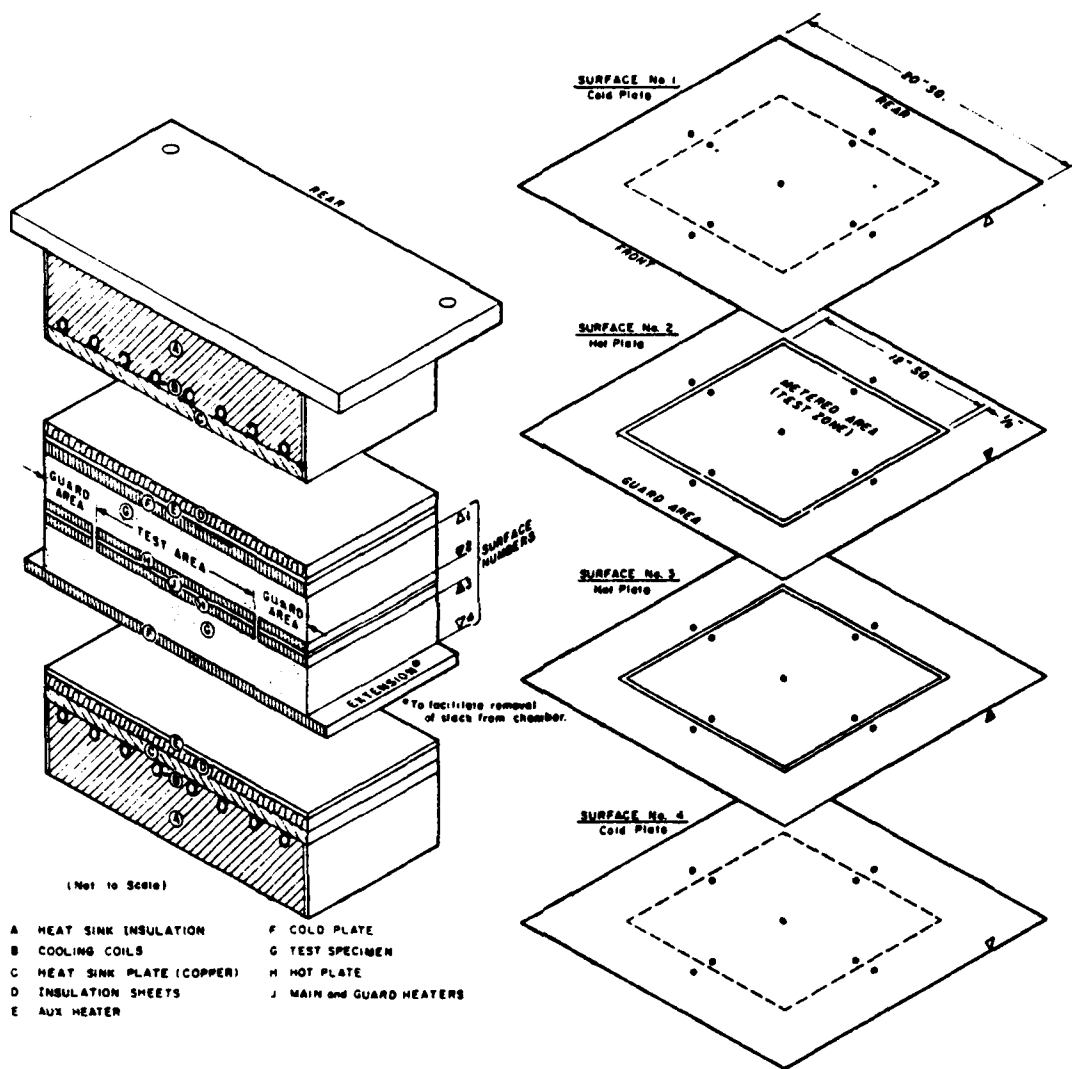


Figure 13. Specific heat of CRREL varved clay.

Sample preparation

Soil for the air-dried Fairbanks silt samples was put through a no. 10 sieve. A phenolic mold 45.7 x 47.7 x 3.2 cm was attached to a bottom plate (surface no. 4 in Fig. 14), and the soil tamped into the mold. To achieve the desired density, the soil was compacted with a mechanical press to approximately 1820 kgf using a 30.5-cm-square plate. A second (top) sample was molded in the same manner except the mold was attached to a plastic-lined molding plate. Then the double center testing plate (surfaces 2 and 3, Fig. 14) was lined with plastic both top and bottom and placed on top of this second sample. This entire assembly for the second sample was then turned completely over and placed on top of the first (bottom) sample. The mold plate was then removed, plastic was put on top of the second (top) sample, and the remainder of the stack (see Fig. 14) was built and placed in the guarded hot plate apparatus. Because of their low moisture content, these samples were frozen in the guarded hot plate apparatus.

Soil for the optimum moisture sample was mixed at 17.3% moisture. The mold was bolted to a plastic-lined cold plate with a 1.27-cm plywood collar clamped to the top of the mold. Soil was placed in the mold in



a. Stack assembly cross section.

b. Thermocouple locations (•) in plate surfaces.

Cross section of stack assembly and thermocouple locations in plate surfaces.

Figure 14. Guarded hot-plate thermal conductivity testing apparatus (ASTM Designation C177-71) (from Kaplar 1971).

approximately three equal layers and hand-compacted with a 7.6-cm-square metal plate. Two samples were made using this procedure. A thermocouple was placed in the corner of one sample at approximately center depth. Freezing curves for the guarded hot plate specimens are shown in Figure 15. After molding, the C-clamps were removed, a sheet of plastic was placed on top of the soil and then the top plate was bolted to the bottom cold plate. Samples were tempered in a 4.4°C coldroom for approximately 24 hours prior to placing them in a -40°C coldroom for a quick freeze.

After freezing, the top cold plate and plywood collars were removed and the samples were milled down to the top of the mold. The bottom test plate was bolted to the top of one sample and the sample flipped; thus the original top of the sample became the bottom of the sample for testing. The other sample was also flipped and became the top sample in the guarded hot plate apparatus.

For the saturated sample, the soil was mixed at 30% moisture content and placed in the mold. However, since the molds were not watertight and the samples shrunk during freezing, they were remolded in large pans, frozen, trimmed on a saw and then their top and bottom surfaces were milled to a height of approximately 5 cm. The samples were sealed in plastic and tested without a mold. The moisture content and density data obtained after the test showed that the samples were not identical. This difference may have been caused by a delay of approximately 10 days from the time the first sample was frozen to the time it was trimmed and tested, as opposed to a one-day delay between freezing and trimming for the second sample.

Only one sample of CRREL varved clay was made for each moisture condition. For the air-dried sample, the material was molded with a mechanical press in three layers. For the optimum moisture sample, the soil was mixed at approximately 20% moisture and hand-compacted lightly with a 91.4-cm-square piece of steel in three layers in a mold attached to the freeze plate. A thermocouple was placed in the corner of this sample at approximately center depth (see Fig. 15 for freezing data). The top freeze plate was attached and the sample placed in a 5.6°C coldroom to temper for approximately three hours. Then the sample was moved to a -28°C coldroom for quick freezing.

After freezing, the top surface was not very smooth and so some dry soil was added, the top scraped off level, and then lightly sprayed with water. This surface became the bottom surface of the tested sample.

For the saturated sample, the soil was mixed at 35% moisture content and then put through a 1.27-cm sieve and allowed to sit overnight. The soil was lightly compacted in an aluminum foil lined pan, with foil placed on top of the soil and then a steel plate placed on top of the foil. The sample was placed on a steel plate on a cart and placed in a 1.7°C coldroom overnight.

A plastic sheet was placed on top of the sample, ice added around the edges, and then the sample was placed in a -1.1°C coldroom for freezing.

After the sample was removed from the pan, and trimmed to 48.3 cm x 48.3 cm, it was iced to a steel plate and the top milled to an even surface. The sample was flipped and again iced to a steel plate and the bottom milled smooth. The sample was once more flipped and the top remilled slightly.

Height and weight measurements were taken and the sample installed in the guarded hot plate apparatus with the original top placed down (toward the cold side) and the standard gum rubber sample used as the second sample in the top.

The two Ottawa sand (20-30) samples were molded as follows. For the air dried sample the bottom thermocouple (TC) testing plate was bolted to the mold and a small bead of silicon rubber was placed around the inside of the mold. Sand was put into the mold and the mold was hand-vibrated by tapping the bottom TC plate to settle the sand.

For the surface wet sample, sand was mixed with distilled water and allowed to sit and soak for approximately 2 hours. The sand was then put into a #30 and/or #40 sieve and the excess water was shaken off. Sand was placed in a mold attached to a freeze plate. A top freeze plate was then bolted to the bottom freeze plate. The sample was then flipped on end and allowed to drain for approximately 10 minutes. The sample was placed upside down in a 4.4°C coldroom for approximately 3 hours and then reflippped (original top was then up) and put into a -9.4°C coldroom to freeze overnight.

After freezing, a new height measurement was taken as the sample was above the mold. Vacuum grease was put on the mold and the bottom thermocouple testing plate and entire sample flipped. The original top was then on the bottom or cold side.

Test procedure

The first samples tested were in accordance with ASTM C177-71 using the guarded hot-plate testing apparatus.

After testing the Fairbanks silt using two identical samples, the top sample was removed and replaced with a standard gum rubber sample. The tests were repeated and the results compared (see Fig. 16).

The remainder of the testing program was concluded using the standard gum rubber sample as the second sample.

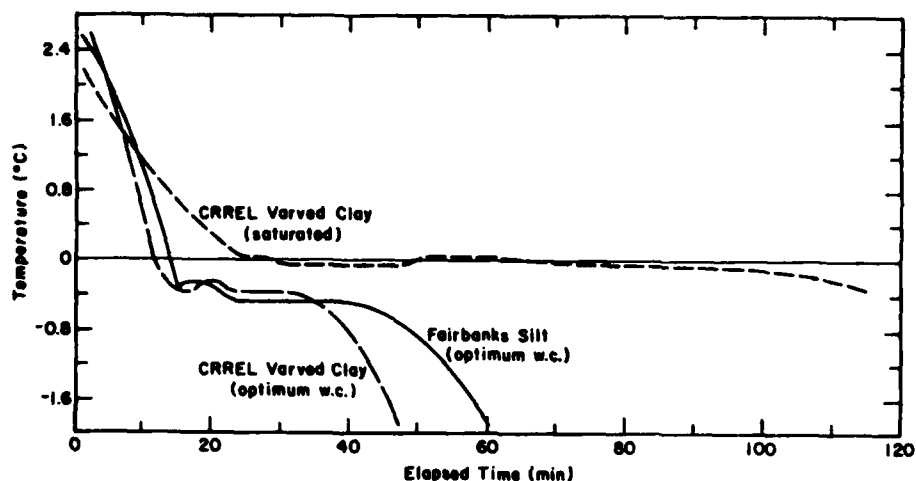


Figure 15. Typical freezing curves for 7.6-cm thick guarded hot plate specimens.

Sample molds

Two molds were constructed of 3.18-cm phenolic cut 2.54 cm wide and 45.7 cm long bolted together at the corners. The bottom side of one mold was tapped so that the testing plate could be bolted to it. The top side of the other mold was also tapped so that the mold plate could be attached. All soil samples had a piece of 4-mil-thick plastic between the sample and the testing plates.

Temperatures

Materials were tested at approximately -10°C , -20°C , -30°C and -45°C with the air-dried materials also tested at approximately $+10^{\circ}\text{C}$. The test results are given in Table 2 and plotted in Figures 16, 17, and 18.

DISCUSSION AND CONCLUSIONS

Specific heat

Use of a differential scanning calorimeter (DSC) to determine the specific heat of frozen soils was done by Kay and Goit (1975). The close agreement between their results and results of other investigations verified the use of such a calorimeter. The comparison of the results of Kersten (1949), Kay and Goit (1975) and this study, shown in Table 3, further confirms the use of this technique. The present DSC setup at CRREL provides a quick and efficient method for determining specific heats.

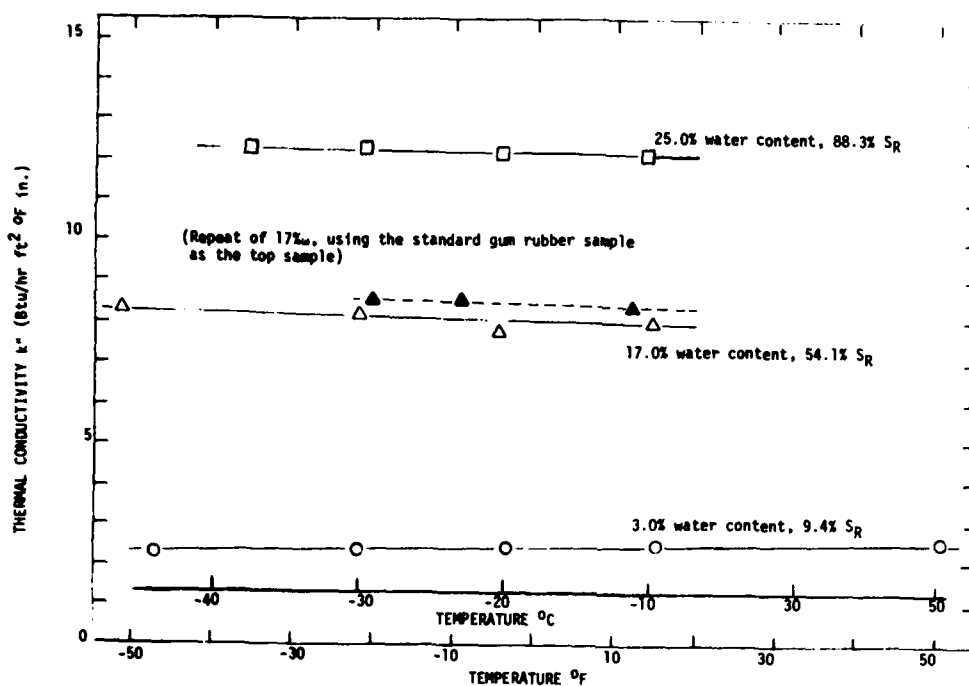


Figure 16. Thermal conductivity vs temperature, Fairbanks silt (S_R = saturation).

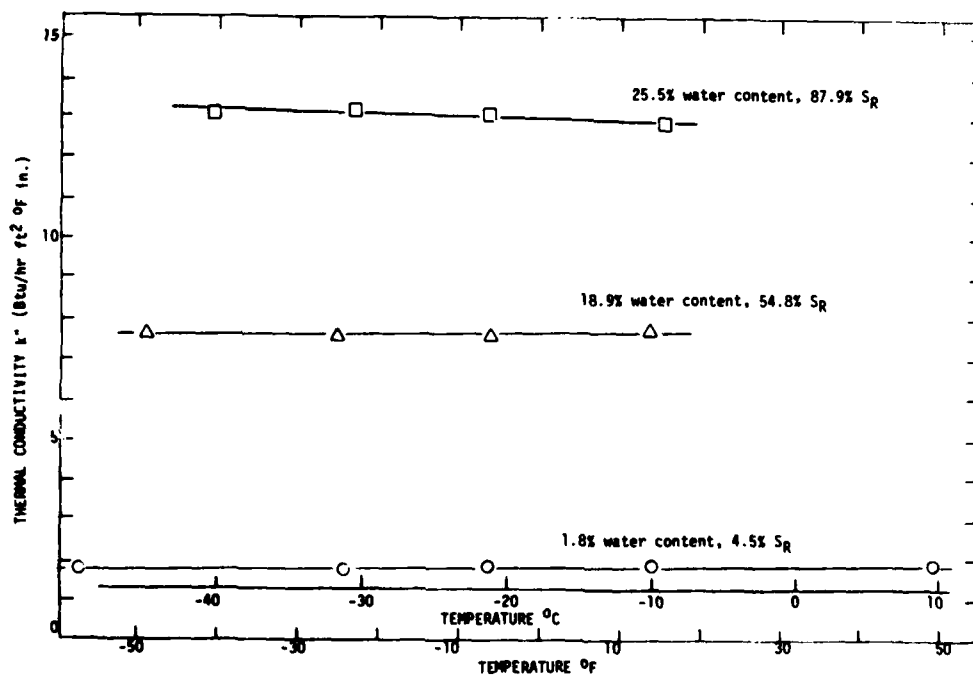


Figure 17. Thermal conductivity vs temperature, CRREL varved clay (S_R = saturation).

Table 2. Thermal conductivity of Fairbanks silt, CRREL varved clay, and Ottawa sand.

| Dry density g/cm ³ (pcf) | Moisture content (%) | Avg. temp. °C (°F) | K Cal/hr cm °C (Btu/hr ft ² °F in.) |
|---|----------------------------|--|---|
| <u>FAIRBANKS SILT (ML)</u> | | | |
| 1.448 (90.5) | 3.0 | 10.3 (50.4) - 9.4 (15.1) -19.6 (3.5) -30.0 (21.9) -44.2 (-47.0) | 3.265 (2.626) 3.110 (2.508) 3.083 (2.486) 3.034 (2.447) 2.967 (2.393) |
| 1.459 (91.2) | 17.0 | - 9.8 (14.4) -20.2 (-4.6) -30.0 (-21.9) -46.6 (-51.1) | 9.879 (7.967) 9.635 (7.770) 10.136 (8.174) 10.301 (8.307) |
| 1.526 (95.4) | 25.0 | -10.3 (13.5) -20.0 (-4.3) -29.7 (-21.3) -37.3 (-35.5) | 14.953 (12.059) 15.060 (12.145) 15.205 (12.262) 15.165 (12.230) |
| 1.459 (91.2) | 17.0 | -11.1 (11.9) -22.6 (-9.3) -29.2 (-20.3) | 10.358 (8.353) 10.643 (8.583) 10.595 (8.544) |
| <u>CRREL VARVED CLAY (CL-ML)</u> | | | |
| 1.302 (81.4) | 1.8 | 9.5 (49.2) - 9.9 (14.1) -20.9 (-6.0) -31.1 (-24.1) -49.5 (-56.9) | 2.425 (1.956) 2.396 (1.932) 2.357 (1.901) 2.316 (1.863) 2.341 (1.888) |
| 1.419 (88.7) | 18.9 | -10.2 (13.7) -20.9 (-6.0) -31.4 (-24.8) -45.2 (-48.6) | 9.593 (7.736) 9.422 (7.598) 9.402 (7.582) 9.513 (7.672) |
| 1.526 (95.4) | 25.4 | -10.6 (12.9) -21.0 (-6.1) -30.4 (-22.8) -40.1 (-40.2) | 15.814 (12.802) 16.189 (13.056) 16.307 (13.151) 16.176 (13.045) |

Table 2. (Cont'd.)

| Dry density g/cm ³ (pcf) | Moisture content (%) | Avg. temp. °C (°F) | K Cal/hr cm ² °C (Btu/hr ft ² °F in.) |
|---|----------------------------|-----------------------|---|
| <u>OTTAWA SAND (20-30)</u> | | | |
| 1.774 (110.9) | 0.01 | 9.4 (49.0) | 2.932 (2.364) |
| | | -10.8 (12.7) | 2.697 (2.175) |
| | | -20.3 (-4.9) | 2.685 (2.165) |
| | | -30.8 (-23.5) | 2.634 (2.124) |
| | | -46.9 (-51.8) | 2.541 (2.049) |
| 1.602 (100.1) | 8.8 | -20.9 (-5.9) | 12.577 (10.143) |
| | | -30.9 (-23.7) | 11.326 (9.134) |
| | | -42.0 (-43.3) | 11.904 (9.600) |

All the above tests were performed using two identical samples according to ASTM.

All remaining tests were performed using a Standard Gum Rubber (NBS calibrated) sample as the top sample.

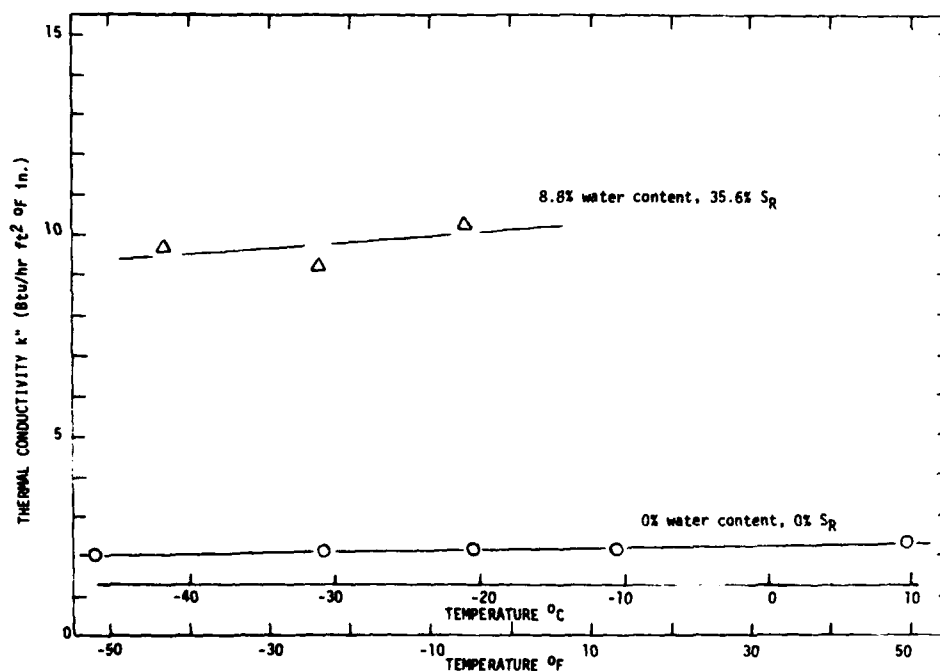


Figure 18. Thermal conductivity vs temperature, Ottawa sand (20-30) (S_R = saturated).

Table 3. A comparison of specific heats of dry soils similar in physical properties to those determined previously by others*.

| Material | Temperature (°C) | Specific Heat (cal/°C g) | References |
|----------------------------|---------------------|-----------------------------|---------------------|
| SAND - Sauble Beach | 17 | 0.174 | Kay and Goit (1975) |
| Northway | 19 | 0.185 | Kersten (1949) |
| Ottawa (20-30) | 18 | 0.164 | Kersten (1949) |
| Lowell | 20 | 0.188 | Kersten (1949) |
| Ottawa (20-30) | 20 | 0.170 | This study |
| Ottawa (50-70) | 15 | 0.165 | This study |
| Ottawa (No. 90 shell) | 15 | 0.157 | This study |
| Manchester fine sand | 15 | 0.168 | This study |
| SILT - Conestoga silt loam | 17 | 0.180 | Kay and Goit (1975) |
| Northway silt loam | 20 | 0.176 | Kersten (1949) |
| Fairbanks silt loam | 19 | 0.183 | Kersten (1949) |
| Fairbanks silt | 20 | 0.201 | This study |
| Cook's silt | 15 | 0.202 | This study |
| Jenks sandy silt | 15 | 0.186 | This study |
| Manchester silt | 20 | 0.181 | This study |

*Kay and Goit (1975) and Kersten (1949) values taken from Table 1 of Kay and Goit (1975).

Specific heats were found for 10 soils over the temperature range from -50°C to 45°C. The heat capacities can be readily calculated using the specific heats in Table 1 and the densities in Table 2. The increase in specific heat with increasing temperature and increasing water content shows agreement with other investigations. Density was not assumed to be a factor in the determination of specific heat. This assumption was also made by Kersten (1949).

The effect of unfrozen water in the frozen soil samples is indicated in Figures 3-13 by a more rapid increase in specific heat between -10°C and 0°C. The solid lines were drawn in the figures to indicate trends only. The dashed lines also indicate trends but there is less certainty with these lines.

Thermal conductivity

The first objective in the thermal conductivity tests was to determine the difference in values obtained by using two methods. The first method was in accordance with ASTM C-177-71, using the guarded hot plate with two soil samples on either side of the hot plate. The second method uses a soil sample on one side of the hot plate and a standard gum rubber sample on the other side. The results, as shown in Figure 16, indicate that the

Table 4. Comparison of thermal conductivities found by Kersten (1949) and this study.

| Material | Dry density (g/cm ³) | Moisture content (%) | Temp. (°C) | K (cal/hr-cm°C) | Reference |
|----------------------|-------------------------------------|-------------------------|---------------|--------------------|----------------|
| Ottawa sand | 1.56 | 0.014 | 4.4 | 2.108 | Kersten (1949) |
| | | | - 3.9 | 2.083 | Kersten |
| | | | -28.8 | 2.009 | Kersten |
| | 1.77 | 0.01 | 9.4 | 2.932 | This study |
| | | | -10.8 | 2.697 | This study |
| | | | -30.8 | 2.634 | This study |
| Fairbanks silt | 1.512 | 13.8 | 4.4 | 8.258 | Kersten |
| | | 13.8 | - 3.9 | 9.027 | Kersten |
| | | 13.7 | -17.8 | 8.705 | Kersten |
| | | 13.7 | -29.3 | 8.767 | Kersten |
| | 1.526 | 25.0 | -10.3 | 14.953 | This study |
| | | | -20.0 | 15.060 | This study |
| | | | -29.7 | 15.205 | This study |
| Fairbanks silty clay | 0.924 | 2.4 | - 4.0 | 1.203 | Kersten |
| | 1.278 | 2.3 | -29 | 2.009 | Kersten |
| CRREL clay | 1.302 | 1.8 | - 9.9 | 2.396 | This study |
| | | | -31.1 | 2.316 | This study |
| Fairbanks silty clay | 1.286 | 17.6 | - 4.0 | 8.023 | Kersten |
| | | 17.6 | -29.0 | 8.010 | Kersten |
| CRREL clay | 1.419 | 18.9 | -10.2 | 9.593 | This study |
| | | | -31.4 | 9.422 | This study |

gum rubber method gave results about 5% higher than those of the method with two soil samples. Since use of the gum rubber greatly facilitated testing and gave results within experimental accuracy, all remaining tests were conducted with the gum rubber.

The results of this investigation are compared to a selection of the results of Kersten (1949) in Table 4. Considering the differences in density and moisture content, there is good agreement. The results as given in Table 4 and plotted in Figures 16, 17, 18 show that there is not much change in thermal conductivity with temperature for the air-dried samples. The data of this study agree with Kersten's (1949) conclusion

for frozen soils that the thermal conductivity increases as the temperature decreases and moisture content increases. He points out that even though the conductivity of the soil solids decreases, the conductivity of the ice increases with decreasing temperature. Kersten (1949) found that the thermal conductivity increased as the density of the soil increased. The data of this study show some agreement with that conclusion.

Thermal diffusivity

It would be useful to make direct measurements such as were done by Higashi (1953) and compare them to the calculated results. However, the thermal diffusivities given in Table 5 were calculated by dividing the thermal conductivity by the specific heat per unit volume for data obtained in this study. In order to find the thermal conductivity for some of the temperatures given in the table, careful interpolation and extrapolation were necessary. Extrapolation was believed justified because the thermal conductivities did not vary much with temperature. Table 5 indicates that the thermal diffusivities all tend to increase with decreasing temperatures and increasing water contents. The thermal diffusivities found in this study are slightly higher than those reported by Higashi (1953). This discrepancy may be explained by the different soil types and moisture contents used in the two investigations.

Table 5. Thermal diffusivity (cm^2/s) $\times 10^{-3}$.

| Sample | Water Content (%) | Temperature ($^{\circ}\text{C}$) | | | | |
|----------------------|-------------------------|------------------------------------|-------|-------------------|-------|-------|
| | | -50 | -35 | -20 | -5 | 20 |
| 20-30 Ottawa sand | 0.01 | 3.02* | 2.85 | 2.88 [†] | 2.73 | 2.81* |
| | 8.8 | 13.17* | 11.77 | 12.45 | -- | -- |
| Fairbanks | 3.0 | 3.37* | 3.19 | 3.30 | 3.10 | 3.03* |
| | 17.0 | 9.49* | 8.22 | 7.78 | 6.79* | -- |
| | 25.0 | -- | 10.05 | 10.02 | 8.04* | -- |
| CRREL varved clay | 1.8 | 3.14 | 2.91 | 2.76 | 2.66 | 2.33* |
| | 18.9 | 8.26* | 8.21 | 7.44 | 6.22* | -- |
| | 25.5 | 12.19* | 11.24 | 10.33 | 8.76 | -- |

* Extrapolated.

[†] For example, 2.88×10^{-3} .

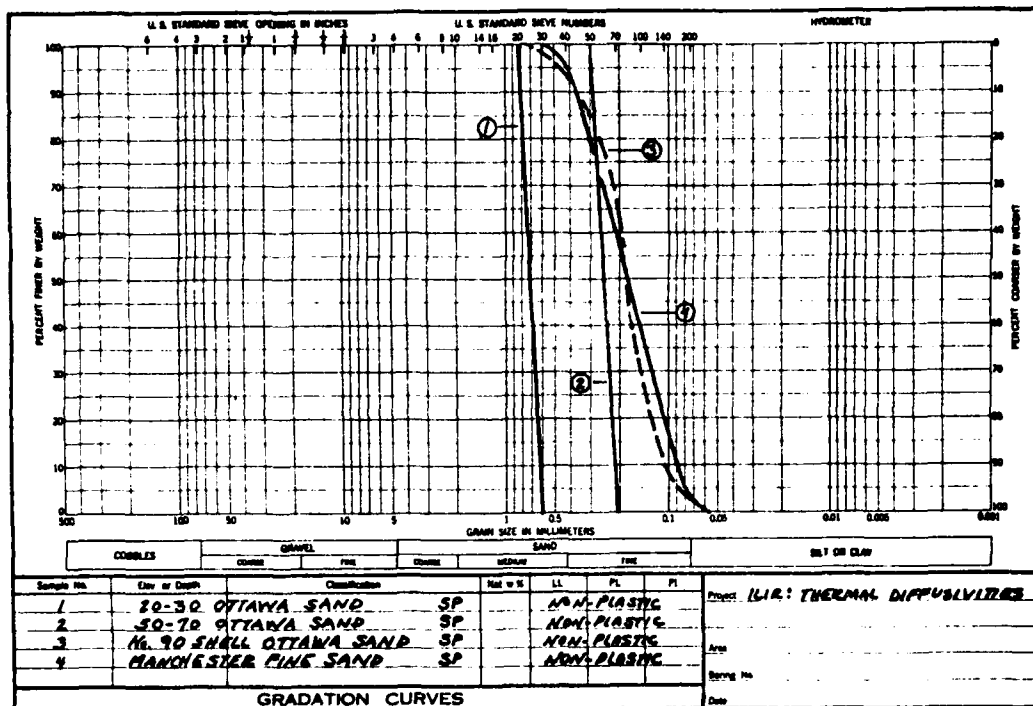
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APPENDIX A: TEST MATERIAL INFORMATION

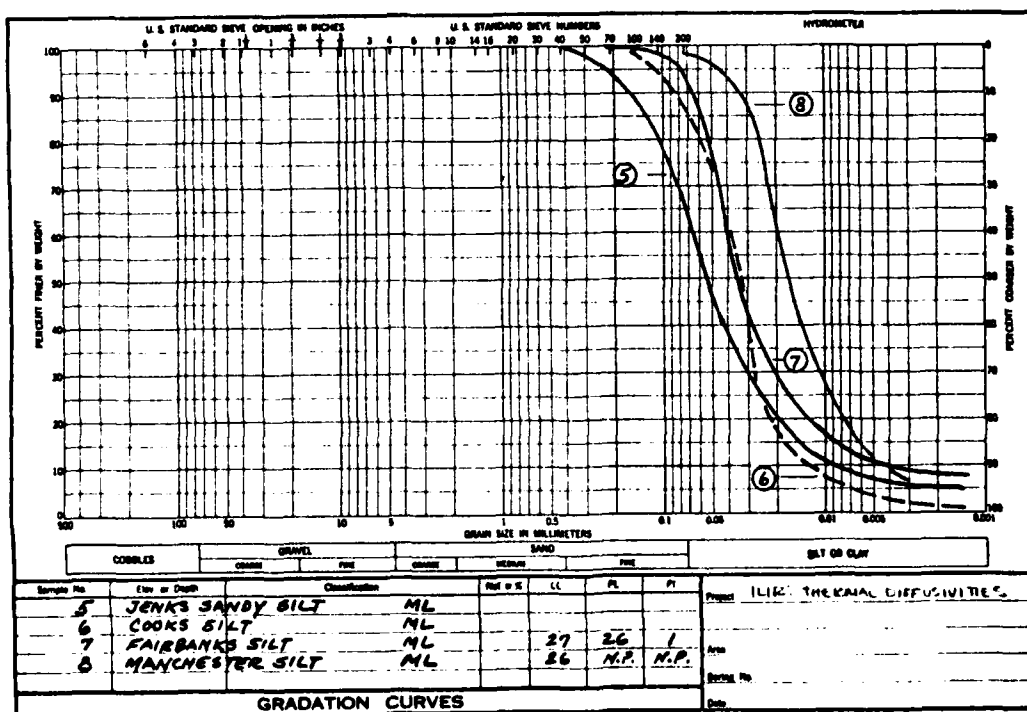
Table A1. Test material information and mechanical properties.

| MATERIAL | SOURCE | TEST PROGRAM | | CLASSIFICATION | SPECIFIC GRAVITY | ATTERBERG LIMITS | |
|-----------------------------|---|---------------|------------------------|----------------------------------|------------------|------------------|------|
| | | Specific Heat | Thermal Conductivities | | | LI. PI. | PI |
| 1. 20-30 Ottawa Sand | Commercial Graded Std. Sand, Ottawa, IL | X | X | SP Poorly Graded (Sorted) | 2.65 | Non-Plastic | |
| 2. 50-70 Ottawa Sand | Commercial Graded Sand, Ottawa, IL | X | | SP Poorly Graded (Sorted) | 2.66 | Non-Plastic | |
| 3. No. 90 Shell Ottawa Sand | Commercial Graded Sand, Ottawa, IL | X | | SP Poorly Graded clean sand | 2.66 | Non-Plastic | |
| 4. Manchester Fine Sand | Manchester, N.H. | X | | SP Poorly Graded clean sand | 2.67 | Non-Plastic | |
| 5. Jenks Sandy Silt | West Lebanon, N.H. | X | | ML Sandy Silt | 2.70 | Non-Plastic | |
| 6. Cook's Silt | Norwich, N.H. | X | | ML Silt | 2.73 | NA | |
| 7. Fairbanks Silt | Fairbanks, AK | X | X | ML Silt | 2.70 | 27 26 | 1 |
| 8. Manchester Silt | Manchester, N.H. | X | | ML Silt | 2.73 | 26 N.P. | N.P. |
| 9. Suffield Clay | Suffield, Alberta (Canada) | X | | Cl., slightly organic clay | 2.69 | 35 20 | 15 |
| 10. CREEL Varved Clay | Hanover, N.H. | X | X | Cl., clay with a few silt varves | 2.78 | 31 24 | 7 |



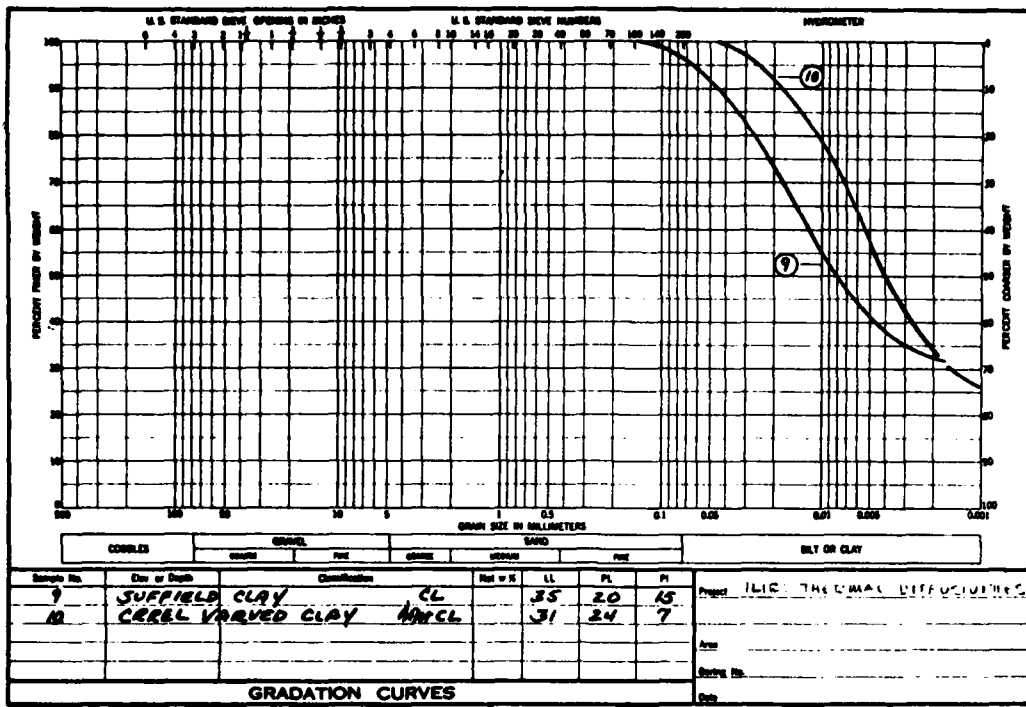
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Figure A1. Gradation curves for sands.



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Figure A2. Gradation curves for silts.



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Figure A3. Gradation curves for clays.

APPENDIX B. CALCULATION OF SPECIFIC HEAT.

1. Place each DSC scan record on a flat surface and draw in base line interpolations for each peak as shown in Figure B1.
2. Select the temperature or temperatures at which the specific heat value is desired, and measure the amplitude of the pen deflection at those temperatures on the sapphire, blank, and sample records.
3. If the blank deflection is in the same direction as the sample and sapphire deflections, subtract the blank deflection from the sample and sapphire deflections. If the blank deflection is in the opposite direction, add it to the sample and sapphire deflections.
4. Obtain the specific heats of the sapphire, at the temperatures of interest, using the supplied table. If the temperature of interest is not included in the chart, a linear interpolation from adjacent values should be used.
5. The specific heat of the sample can now be obtained by applying the formula:

Specific heat (sample) =

$$\frac{\text{Amplitude (sample)}}{\text{Amplitude (sapphire)}} \times \frac{\text{Weight (sapphire)}}{\text{Weight (sample)}} \times \text{specific heat (sapphire)} \quad (\text{B1})$$

Example calculation:

Calculation of the specific heat of 50-70 Ottawa sand at 6.6% water content, (OWS-3) is as follows:

Refer to Figure 5, at -50°C, substitute the mV values from the recorder traces to eq B1.

Amplitude of sample = 0.564 mV - 0.088 mV (blank run correction)

Amplitude of sapphire = 0.468 mV - 0.088 mV

Weight of sapphire = 26.5 mg

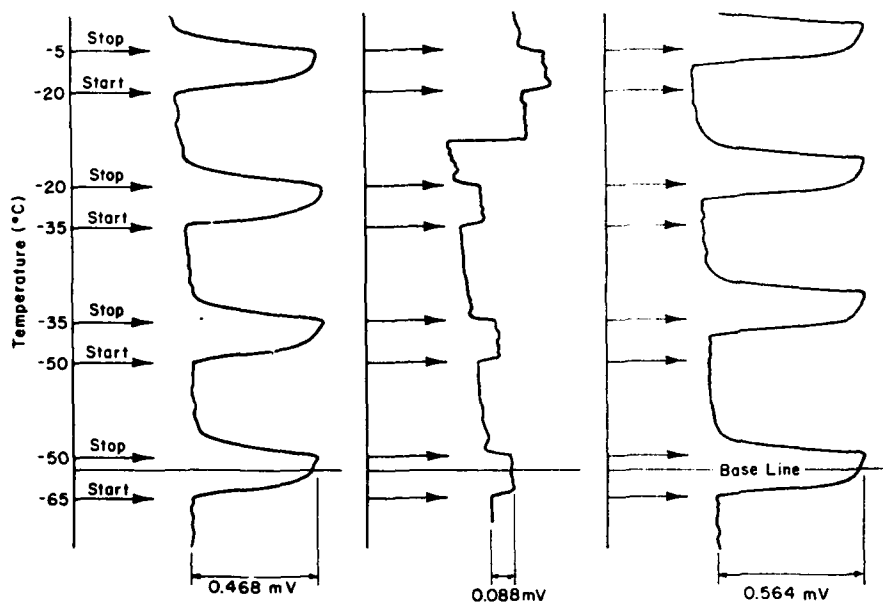
Weight of wet sample (from Table 2) = 29.1 mg

Specific heat of sapphire at -50°C (from sapphire calibration chart) =

$$0.13799 \text{ cal } ^\circ\text{C}^{-1} \text{ g}^{-1}$$

Therefore:

$$\frac{0.564 - 0.088}{0.468 - 0.088} \times \frac{26.5 \text{ mg}}{29.1 \text{ mg}} \times 0.13799 \text{ cal } ^\circ\text{C}^{-1} \text{ g}^{-1} = 0.157 \text{ cal } ^\circ\text{C}^{-1} \text{ g}^{-1}.$$



a. Sapphire crystal run. b. Blank run (empty pans). c. 50-70 Ottawa sand (OWS-3).

Figure B1. Reductions of actual recorder mV outputs, showing partial temperature scans used in computing the specific heat of 50-70 Ottawa sand (OWS-3) at 6.6% water content.

